

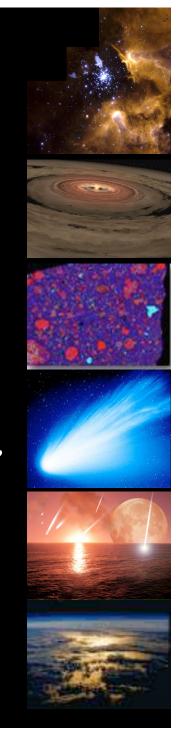
Karen Meech Univ. Hawaii NASA Astrobiology Institute

Meeting Goals

- Discuss issues related to the origin of water on Earth
- Identify key unanswered questions
- What are the key chemical/dynamical clues?
- Identify areas where interdisciplinary research will help the field.

Organizing Committee

- K. Meech, M. Mottl, N. Haghighipour (UH)
- Steve Mozjsis (UCO)
- Mike Mumma (Goddard)
- Ed Young (UCLA)





Molokai Agenda Feb 28, 2008

Bergin	UMich	Disk Physical Structure and Water chemistry		
Keane	IfA	Deuteration in the Solar Nebula – Chemical Ice Models		
Keil/Krot	UH	Aqueous Alteration of Asteroidal Meteorites		
Young	UCLA	Oxygen Isotope Signatures in the Nebula and Implications for Water		
Drake	AZ	Nebular Origin of Water by Gas Adsorption		
Mumma	GSFC	Comet Composition, Dynamical Mixing in Nebula		
Meech	IfA	Activity in Small Bodies, Evidence for Ices		
Jewitt	IfA	Main Belt Comets		
Morbidelli	Nice	Terrestrial Planet Formation and the Late Heavy Bombardment		

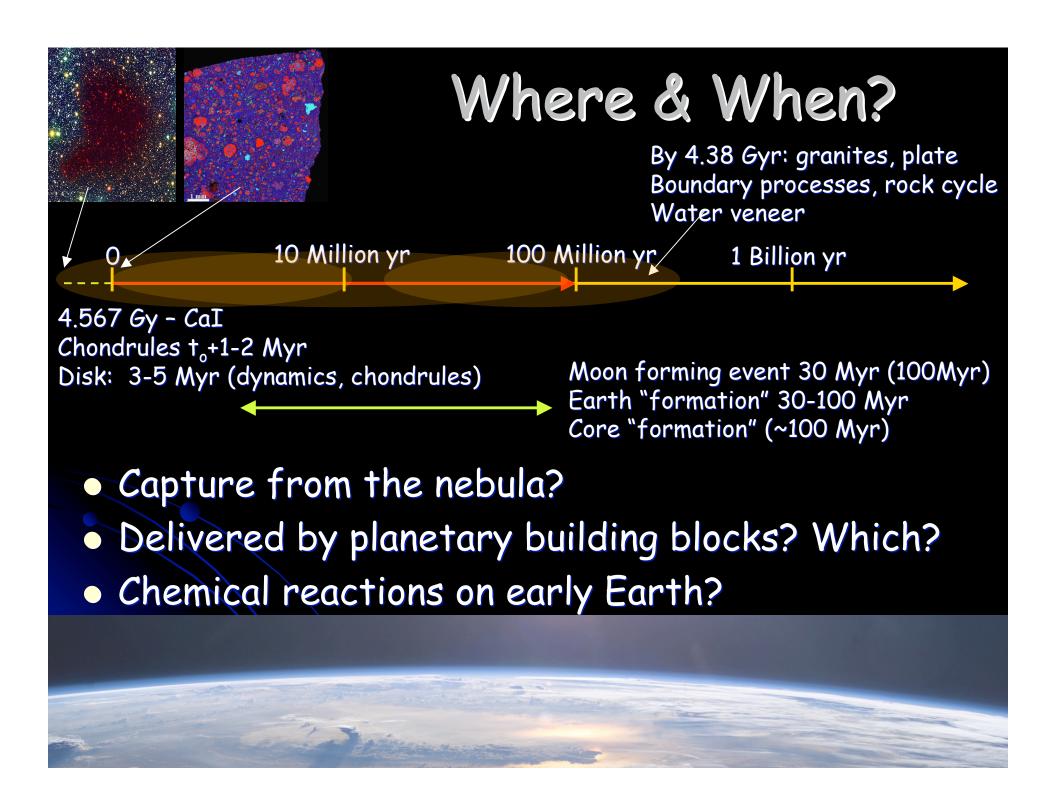
Molokai Agenda Feb 29, 2008

Marty	CNRS	Evolution of the Mantle and Atm on Earth wrt Water		
Stevenson	Caltech	Early Earth Degassing		
Smyth	U. CO	Hydration State of the Mantle		
Yokochi	Univ. Chic.	Time Constraints on Early Earth's Events: Degassing and Volatile Escape		
Mojzsis	U. CO	Water Crust Interactions on Hadean Earth		
Korenaga	Yale	Earth's Regassing History: Constraints from Global Thermal and Chemical Budgets		
Genda	Tokyo Inst.Tech	Nebular Origin of Water on Earth		
Owen	IfA	Contributions from Comets		
Dauphas	Univ. Ill	Origin and Evolution of Terrestrial Volatiles		

What Do we Want to Know?



- How much water is in Earth, and was on Earth at start?
- When and how did the water come?
- What are the chemical and dynamical fingerprints of this process?







 $Atm H_2 + O \rightarrow H_2O$

A O

Magma ocean oxides: FeO

Hadean Earth

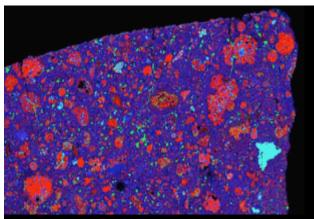
- Heat from impacts
 - Melts surface of Earth -"magma ocean"
- Earth captures a H_2 Atm gases react \rightarrow form water



Insights from Protoplanetary Disk

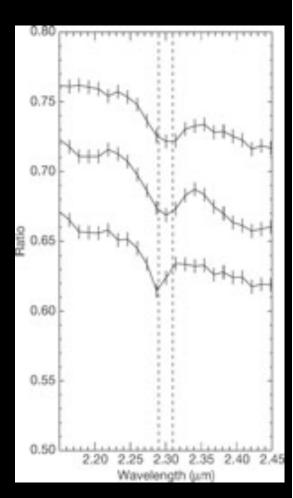
- Water was present at all stages of disk but in various states (ice, gas, liquid)
- D/H fractionation in disk (heavy chemical processing)
 - Likely that it will be high, with strong radial gradients
 - Expect comets / icy bodies forming at different distances to be quite different in D/H
 - No observations yet of D/H gradients in disks technology limit - will come within next 5 years
- Debate over the location of the "snow line"
 - Disk models can have it as close as 1AU → Moves over time
 - Dynamics and growth of Jupiter → near 5 AU in our SS
 - Extra source of heat in our SS (formed in a cluster)





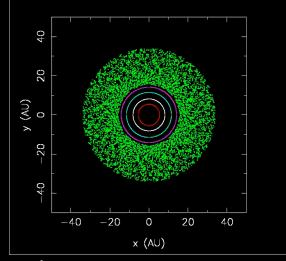
Key Insights from Cosmochemistry

- 15 groups of chondrites each from a single asteroid (we have insufficient samples)
- Aqueous alteration was everywhere as seen in meteorite collection - some more than others
 - This indicates snow line farther out cannot bring water in later
 - This level of aqueous alteration can't be from gas adsorption alone
- Photochemistry probably produced large ¹⁸O/¹⁶O and ¹⁷O/¹⁶O gradients in the disk
 - \bullet Δ^{17} O was a tracer for water-rock interactions in the inner solar system
- Key question how water-rich were the planetesimals and where in MB - look for evidence of hydration on surface



Mars Express, Poulet (2005), Nature

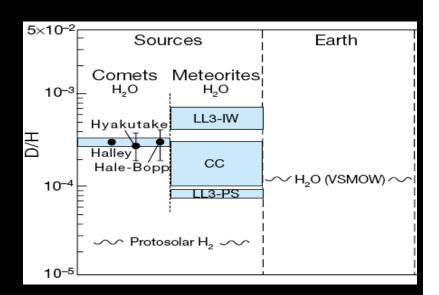
Planet Formation & Dynamics

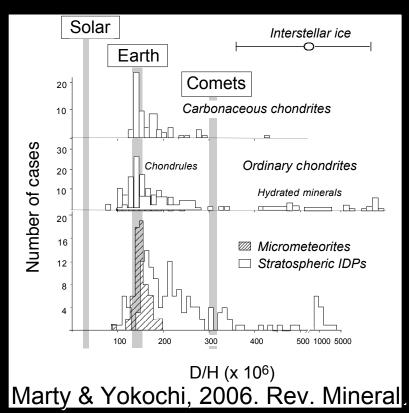


- Eccentricity of Jupiter's orbit is important to the argument of where the wet planetesimals came from that built earth
 - if circular, then 10-15% came from 3.5-4.0 AU the late veneer
- Terrestrial feeding zone moves out with time
 - started with material near Earth (we don't have this any more)
 - water came later in game
- The only comets likely to deliver water to Earth came from farther out the KBO region
- LHB event can trap KBO material in the main belt (D type? MBC?)

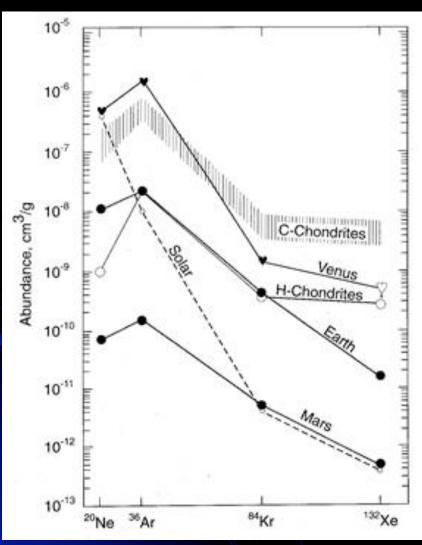
D/H in Small Bodies

- Isotopic tracers: D/H
 - Earth $\sim 16 \times 10^{-5}$
 - Solar System ~ 2.5 x 10⁻⁵
 - Comets $\sim 30 \times 10^{-5}$
- Problem with comets
 - D/H high not sole source
 - Dynamically easier to bring from Asteroid belt
 - Have measurements from only 3
 - Have several classes of comets - only sampled 1





Problems with Meteoritic Carriers



- D/H matches Earth
- Noble gases do not
- Carbonaceous chondrites have Xe 20x more abundant wrt Kr than on Earth
- Amount of trapped noble gases should increase with distance from sun

Os Isotope Dilemma?

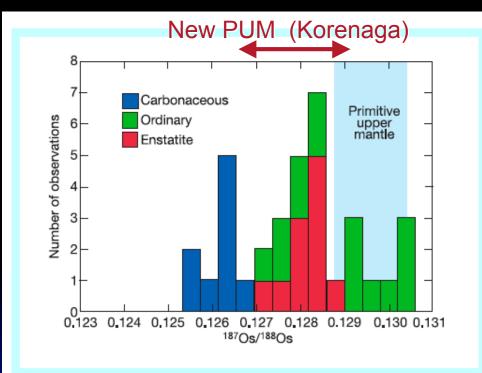
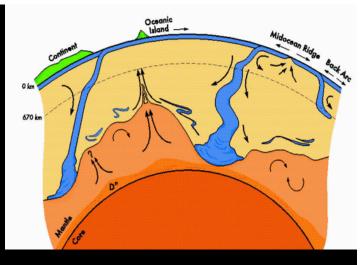


Figure 4 187 Os/ 188 Os ratios in carbonaceous, ordinary and enstatite chondrites, and in the Earth's primitive upper mantle. The ratios are distinct and are diagnostic of the nature of the Earth's 'late veneer' 43 . Mars is not plotted because the uncertainty in its initial 187 Os/ 188 Os ratio is larger than the range of the x axis.

- Chondrite classes have different Os isotope signatures
- CCs are wet (~10wt% water), others dry (<1%)
- OCs used to match Earth
 → but this has been revised.

[Drake and Righter, Nature, 2002]

Earth Signatures



- Minerals fractionate D/H if earth started at protosolar value, there should be a reservior of light H in the interior
- D/H inside earth probably not coupled to surface water.
- Early atm mass fractionation of Xe
- D/H in organics in sedimentary rock constant for past 3.5Gy
- 10 Myr after moon form event ocean-ocean subduction set in (min value)
- Clear evidence of solar nebula Ne in Earth interior ingassing from SN via magma ocean



How Much water?

Region	Low Ocean	High Ocean	Capacity
Ocean/Atm	1.32	1.32	1.32
Crust	0.02	0.10	0.1
Lithosphere	0.04	0.49	3.3
Mantle	0.04	4.2	15.1
Core	0.03	2.8	28.1
TOTALS	1.5	11.2	59.7

What do we Know? We Need more Constraints

- Know of ~3 reservoirs of N and of D/H in 55
- Comets chemically are being divided into classes
- Getting a better understanding of disk models
- Better understanding of how to make a SS dynamically
- Unmistakable signature of He and Ne from solar nebula in Earth interior
- H is a trace element in the bulk silicate Earth
- Earth suffered massive volatile loss at multiple episodes

It is likely Earth acquired water by more than one means - it is an issue of relative quantities

Workshop Key Measurments

'So, we spent 2.5 days deciding we don't know anything....." [Mike Drake]

- D/H gradients in disks verify chem models (ALMA comes on line)
- Most staggering lack of data: comets (based on lab expts)
 - D/H and measurements will be highly valuable to a number of stories
 - Observing a new class of objects in the MB will be compelling
 - Noble gases in comets (Ar, Xe) could address late veneer and Earth/Mars Xe deficit
 - Comet N isotope measurements in NH₃ if like Earth, unlikely comets brought much water.
- Would like to know bulk Earth D/H is there an accessible primordial reservoir of water?

Now What?

- Presentations
 - Origins of Oceans Public Event
 - M. Drake Invited Seminar in G&G / Astrobio in HI
 - M. Mottl talk at this meeting
- Working on a group summary paper
- Many new collaborations have started
 - Smyth & Yokochi new reservoir of Xe
 - UHNAI Smyth a collaborator
 - Many more . . .

